

active. These transfer zones were affected by uplifts and inversion structures.

In the Late Middle Pleistocene to Present extensional basins and transfer zone formed. Intense volcanism and eastwards migration of the extension was recorded in the northern Campania Margin. NNE-trending normal faults developed in the ETM and Apennines and this extensional pattern is coherent with the migration of the Calabrian accretionary prism toward E-SE. During this tectonic stage, a NW-SE transfer zone, featuring restraining and releasing bends, formed at the SW border of the ETM.

The deformation features of the upper plate in correspondance of the ETM are not consistent with the current rifting models. We hypothesize a link between the evolution of upper plate and subducting slab. The proposed geodynamic scenario is characterized by the formation of extensional basins in the upper plate and onset and development of a STEP (Subduction-Transform-Edge-Propagator) fault along the northern margin of the Ionian slab.

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WHAT DRIVES ALPINE TETHYS OPENING: SUGGESTIONS FROM NUMERICAL MODELLING

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Introduction. Continental crustal slices, preserving pre-Alpine metamorphism, are widely described in Alps and Apennine realms (Fig. 1). Variscan-age eclogites (430-326 Ma) generated from continental, oceanic and mantle rocks occur within these slices and suggest

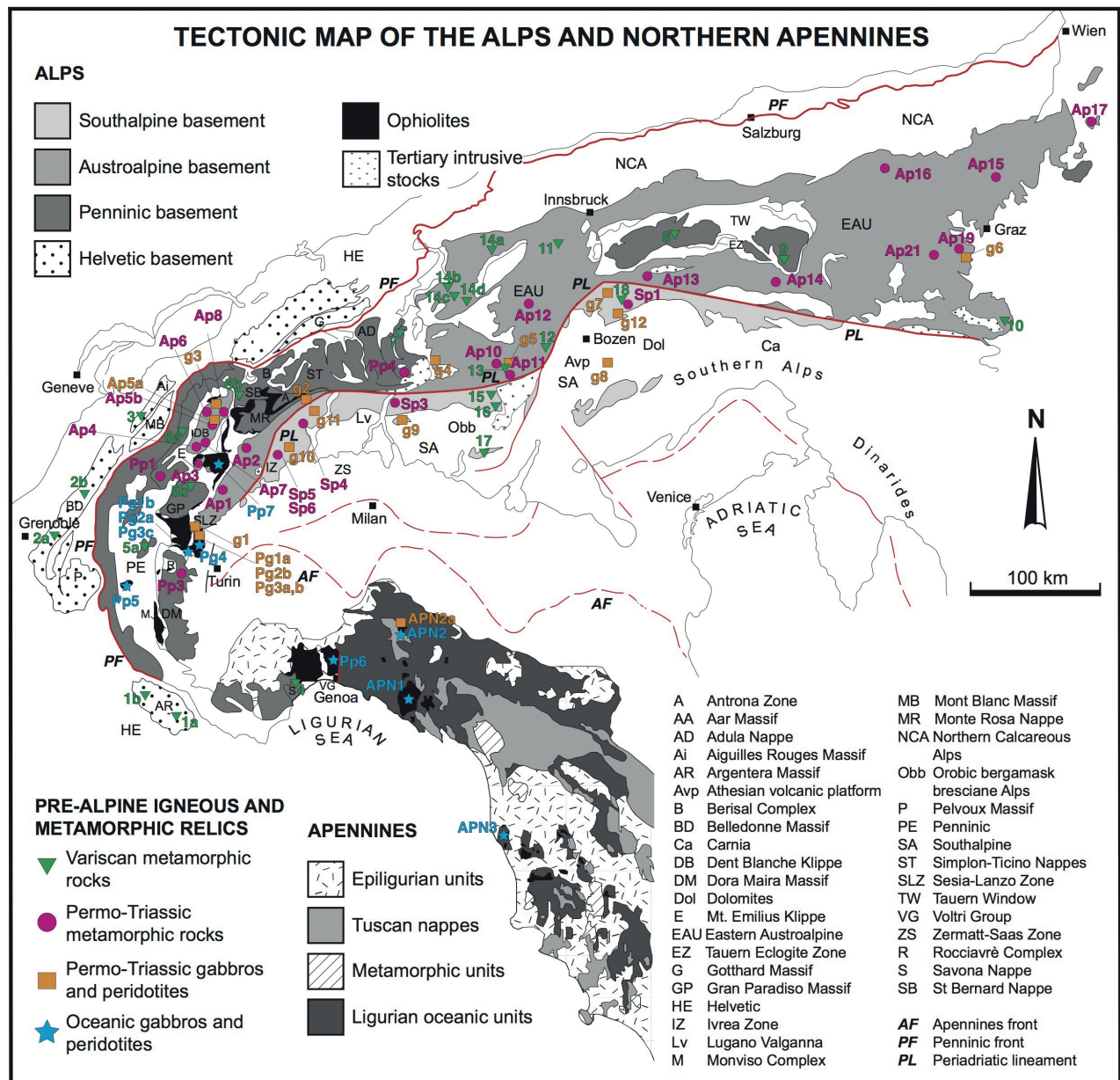


Fig. 1 – Tectonic outline of the Alps and northern Apennines with the locations of igneous and metamorphic pre-Alpine relicts as labeled in Spalla *et al.* (2014) and Marotta *et al.* (2016).

a pre-Alpine burial of continental crust at convergent plate margins, in a context of oceanic lithosphere subduction underneath continental upper plate, characterized by a low thermal regime, and followed by continental collision (e.g. Marotta and Spalla, 2007; von Raumer *et al.*, 2013; Spalla *et al.*, 2014). Permian-Triassic remnants (300-220 Ma) of high-temperature metamorphism, mainly occurring within Austroalpine and Southalpine domains (belonging to Adria plate) and associated with widespread basic to acidic igneous activity testified by large gabbro bodies (Fig. 1), indicate an increase of the lithospheric thermal regime (e.g. Lardeaux and Spalla, 1991; Schuster and Stüwe, 2008; Marotta *et al.*, 2009; Spalla *et al.*, 2014) related to asthenospheric upwelling and lithospheric thinning (e.g. Thompson, 1981; Sandiford and Powell, 1986; Beardmore and Cull, 2001). During Late Triassic-Early Jurassic an important extensional stage leads to the break-up of the Pangaea continental lithosphere and the opening of the Alpine Tethys Ocean, accounted by the occurrence of ophiolitic sequences in the western Alps and Apennines (Fig. 1). The geodynamic significance of the Permian-Triassic high temperature and low pressure metamorphic event has been widely debated and recent numerical models suggest an origin consequent to successive lithospheric extension and thinning events

leading to the Mesozoic continental rifting (e.g. Marotta and Spalla, 2007; Marotta *et al.*, 2009; Spalla *et al.*, 2014), whereas on the basis of recent paleogeographic reconstructions it has also been interpreted as engaged by the neo-Variscan late-orogenic collapse (e.g. Spiess *et al.*, 2010; von Raumer *et al.*, 2013). In the northern Atlantic region for instance, a sequence of rift basins from Permian to Cretaceous has been described occurring before the opening of the ocean (e.g. Doré and Steward, 2002) making the rifting of the North Atlantic Ocean a long lasting process with several extensional events associated with a migration of eulerian poles as testified by the anticlockwise and successive clockwise rotation of superposed rift axes.

Based on this idea, we test whether the lithospheric extension can lead the rifting of the Alpine Tethys by comparing numerical modelling of post-collisional extension and successive rifting and oceanization with Permian-Triassic to Jurassic natural data from the Alps and northern Apennines (Fig. 1). In particular, we focus our attention on the thermal state of the pre-rifting (Permian-Triassic in age) lithosphere in order to explore if the opening of the Alpine Tethys started on a stable continental lithosphere or rather developed on a thermally perturbed one.

Results. We here discuss the results obtained for two subsequent numerical models that simulate the evolution of the European lithosphere from the late collision of the Variscan chain to the Jurassic opening of the Alpine Tethys. The first model accounts for the evolution of the crustal lithosphere after the Variscan subduction and collision (300 Ma) up to 220 Ma (Marotta *et al.*, 2009). The second model accounts for the rifting of the continental lithosphere from 220 Ma up to reach the crustal breakup and the formation of the oceanic crust (Marotta *et al.*, 2016). For both models different initial geodynamic configurations have been tested and we compare the results with natural data of Permian-Triassic metamorphic rocks and Jurassic gabbros and peridotites (Fig. 1), in order to evaluate which configuration best matches the observations. Natural data belong to different structural Alpine domains. Continental rocks are collected from Helvetic and Penninic domains (European paleomargin) and from Austroalpine and Southalpine domains (Adriatic paleomargin) and oceanic rocks are collected from Alpine and Apennine ophiolites (Fig. 1). The comparison is made in terms of contemporaneous agreement to lithology, pressure and temperature values, and ages. The differences between model predictions and natural P-T-age data are synthesized in Fig. 2, where the ages estimate for the rocks are shown using light grey bars for radiometric ages and dark grey for geologically determined ages.

For the first model we compare the results of two different configurations. The first one is characterized by a purely gravitational evolution of the lithosphere in order to simulate a late-orogenic collapse. The second configuration instead, is characterized by a forced extension of the lithosphere of 2 cm/yr. With respect to the purely gravitational simulation, for which the fit between predictions and observations is obtained for few data only (Fig. 2), the forced extension simulation agrees well with all collected natural data (Fig. 2). The most peculiar character of the Permian-Triassic igneous activity is the widespread emplacement of gabbro stocks at the base of the crust and the occurrence of basaltic products in the volcanics. Therefore, we verify whether the P-T conditions predicted for the lithospheric and asthenospheric mantle by different configurations cross the solidus of peridotite. Although predictions from all configurations satisfy the thermal state for mantle partial melting, the latter is attained at 75 km depth for the purely gravitational configuration and at 50 km depth for the simulation with forced extension. Basaltic melt production is thus compatible with all the simulated tectonic settings but, to allow the partial melting of the continental crust, the thermal state must be similar to that suggested by simulation with forced extension. The final thermo-mechanical setting is very different between the two configurations. In the purely gravitational simulation both the crustal thickness and the lithospheric thermal state are similar to the initial conditions, while in the forced extension simulation a strong lithospheric thinning occurs together with a hot thermal state.

The second model simulates the extension of the continental lithosphere up to reach the

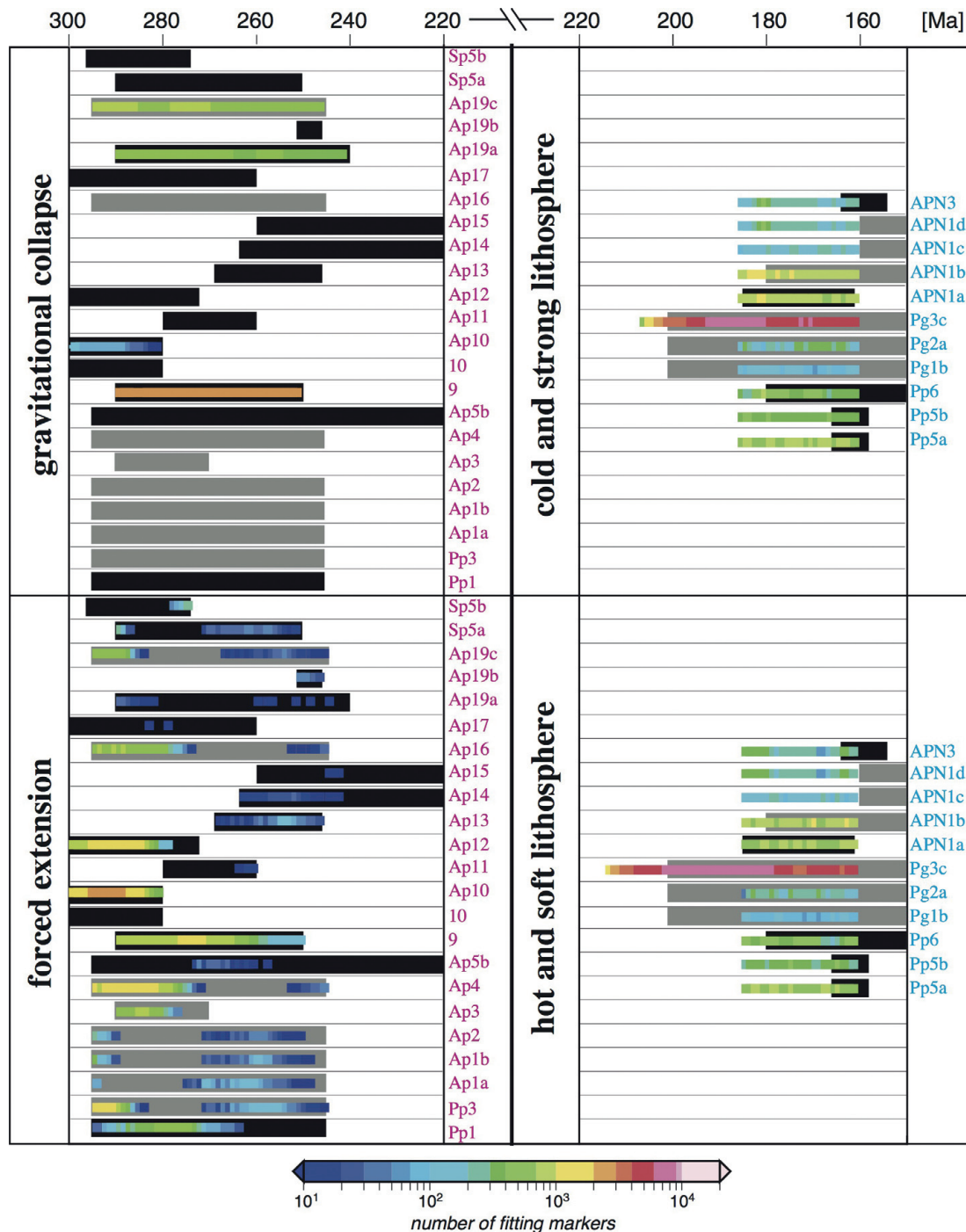


Fig. 2 – Duration of the agreement between the predictions and the natural data as well as number of fitting markers (colors) in terms of lithological affinity and coincident P–T values compared to the radiometric (black thick segments) and geologic (grey thick segments) ages of the natural data. Panel (a) refers to the hot simulations, whereas panel (b) refers to the cold one. The labels are defined in Fig. 1.

crustal breakup and the formation of the oceanic crust. The model also includes the hydration of the uprising mantle peridotite and the extension rate is constant and fixed to 1.25 cm/yr on the both sides of the domain (total extension rate of 2.5 cm/yr). Accounting for two different thermal configurations of the lithosphere allows to constrain two different pre-rifting settings of the Alpine lithosphere (hot and cold simulations with 1600 K isotherm at 80 and 220 km depth respectively). The model results in a symmetric rifting of the continental lithosphere and shows the exhumation of a serpentinized lithospheric mantle (ocean-continent transition zone – OCTZ). The onset of the lithospheric thinning strongly depends on the initial lithospheric

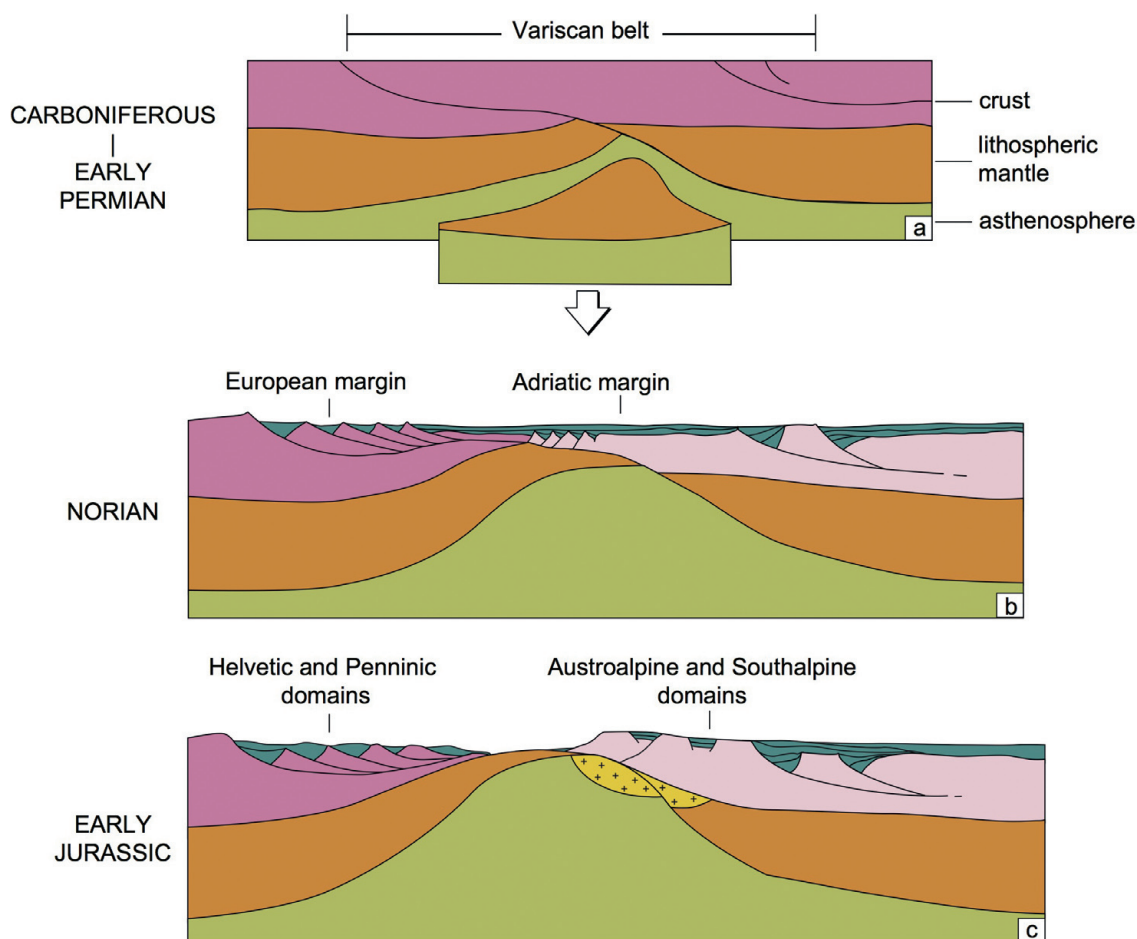


Fig. 3 – Schematic geodynamic cartoon illustrating some stages of the proposed transition from late collisional slab breakoff after the Variscan subduction to Jurassic ocean opening. Legend: pink = Variscan continental crust (dark = European; light = Adriatic); orange = lithospheric mantle; light green = asthenosphere; yellow = area of mantle partial melting generating oceanic gabbros; dark green = Permian-Jurassic sediments.

thermal state: for a cold and strong lithosphere, the thinning is very rapid (4.4 Ma) with respect to a hot and weak lithosphere (15.4 Ma). Similarly, the occurrence of the crustal breakup is shorter for a cold lithosphere (7.4 Ma) than for a hot lithosphere (approximately 31.4 Ma). For both the chosen initial thermal configurations of the lithosphere, the exhumation of the serpentinized mantle starts before the oceanic spreading and the mantle partial melting, making the model compatible with a magma-poor rifting, as suggested for the Alpine case (e.g., Manatschal *et al.*, 2015). In the hot configuration the continental crust thickness sensibly decreases during the extension from 30 km to approximately 5 km close to the OCTZ. In the cold model instead, the crustal thickness decreases from 30 km to approximately 20 km. The comparison between the natural data and the model predictions shows a good agreement with all of the oceanic data for both hot and cold configurations. Taking into account that a hyperextended system has been proposed for the Alpine Tethys rifting (e.g. Manatschal *et al.*, 2015) and a time span of approximately 30-40 Ma is considered between the first extensional structures related to the rifting (200 Ma, Mohn *et al.*, 2012) and the oceanic gabbros emplacement (170-160 Ma, see review in Marotta *et al.*, 2009, 2016), a rifting developed on thermally perturbed lithosphere better agrees the natural data available in ophiolites.

Discussion and conclusion. The comparison between Permian-Triassic to Jurassic natural data from the Alps and the northern Apennines and two subsequent numerical models simulating the evolution of the lithosphere from the late collision of the Variscan chain to the Jurassic opening of the Alpine Tethys suggests that: i) a forced extension of the lithosphere results in a thermal state that better agrees the Permian-Triassic high temperature event(s) than a solely

late-orogenic collapse; ii) a rifting developed on a thermally perturbed lithosphere agrees with a hyperextended configuration of the Alpine Tethys rifting and with the duration of the extension up to the oceanization. These results suggest that the Alpine Tethys rifting and oceanization developed on a lithosphere characterized by a thermo-mechanical configuration consequent to a post-Variscan extension affecting the European realm during Permian and Triassic. Therefore, a long lasting period of continuous active extension can be envisaged for the breaking of Pangea supercontinent, starting from the unrooting of the Variscan belts (300 Ma, Fig. 3a), followed by the Permian-Triassic thermal peak highlighted by HT-LP metamorphism and gabbros emplacement (Fig. 3b), and ending with the crustal breakup and the formation of the Alpine Tethys ocean (170-160 Ma, Fig. 3c). This process could be characterized by alternated period of active extension and stasis, as proposed for the Northern Atlantic rifting or as envisaged for the Ivrea-Verbano Zone on the basis of three metamorphic ages (Permian, Triassic and Jurassic; Langone and Tiepolo, 2015). In order to explore this issue a continuous and polycyclic numerical model is necessary to record the thermo-mechanical inheritance of different events during the entire extensional process, and use ages and P-T-t paths of natural data as constraints.

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